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THESIS

**POWER AND ENERGY STORAGE REQUIREMENTS
FOR SHIP INTEGRATION OF SOLID-STATE LASERS
ON NAVAL PLATFORMS**

by

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June 2016

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INTEGRATION OF SOLID-STATE LASERS ON NAVAL PLATFORMS**

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ABSTRACT

The United States Navy's interest in high-energy lasers (HELs) dictates the need for further study into the propagation of laser light through different atmospheric conditions. Due to the amount of energy required to power these laser weapons systems and the limited amount of available energy onboard ships, different energy storage systems need to be explored.

For this research, two locations were studied: the coast of Cuba and the coast of Russia. These two locations were studied during moderate winter conditions for varying laser output power: 150 kW, 500 kW, and 1 MW. The laser performance code ANCHOR was used to estimate the number of successful HEL engagements that can proceed against a certain target using various configurations of energy storage as the laser output power is varied.

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LIST OF ACRONYMS AND ABBREVIATIONS

DE	directed energy
FEL	free electron laser
HEL	high-energy laser
LaWS	Laser Weapons System
LEEDR	laser environmental effects definition and reference
SOC	state of charge
SSL	solid-state laser

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I. INTRODUCTION

Directed energy (DE) weapons will be an integral part of the future battlespaces. Since HEL engagements cost only dollars per shot and travel at the speed of light, they may provide the U.S. Navy with the upper hand in many scenarios. The Navy recently deployed its first Laser Weapon System (LaWs) on USS Ponce (LPD 15) in 2014. The successful employment of this weapon has demonstrated to the armed services and the public that HELs are viable weapon systems.

This thesis will investigate the effects of thermal blooming and certain atmospheric conditions for various laser power levels as well as the pros and cons of different energy storage methods. The laser output powers of interest are 150 kW, 500 kW, and 1 MW. The atmospheric data will come from laser environmental effects definition and reference (LEEDR), which is a program that characterizes the atmosphere based on gathered data for various locations and conditions. The performance of these lasers in different atmospheric conditions will be evaluated using ANCHOR, a code developed by the Directed Energy Group at the Naval Postgraduate School. The overall number of shots for a given energy storage system, lead acid or lithium-ion, will also be studied using ANCHOR. The purpose of this analysis is to compare how the number of shots per energy storage system is affected by the laser output power, engagement geometry, and the weather.

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II. OVERVIEW OF DIRECTED ENERGY

A. HISTORY

The desire to use laser weapons for the engagement of enemy threats has been around for decades. There are many types of laser technologies that could be used for weapon systems, including chemical lasers, solid-state lasers (SSLs), and free electron lasers (FELs). A laser's ability to engage a target at the speed of light and destroy it for only a few dollars per shot is a benefit that cannot be ignored. There have been numerous programs, some more successful than others, that have tried to implement HELs as weapon systems on various types of platforms for use against enemy targets. The purpose of this study is to explore possible near-term solutions and study the pros and cons of each.

B. ADVANTAGES AND DISADVANTAGES

To fully understand the benefits of HELs, some of the limitations of kinetic weapons should first be considered. Traditional kinetic weapons tend to cost on the order of hundreds of thousands to millions of dollars per engagement, and once the ordinance is expended, there is no way of replenishing the magazine while out to sea. Kinetic energy weapons travel at speeds two to three times the speed of sound, but so do their possible targets, so the target may not be destroyed far enough out to prevent collateral damage to the engaging platform even with the destruction of the target. Also, certain targets can use the transit time to out-maneuver the weapon. Considering the limitations of kinetic weapons, it is easy to see why a weapon that travels at the speed of light is in such high demand. Another key benefit is that lasers are all-electric weapons, so their magazine is only limited by the available electric power. In order to successfully employ an HEL on a naval platform, an energy storage system will likely be required, since the ship may not be able to provide the instantaneous power needed to fire the weapon. Another benefit of having an energy storage system is that it would allow the weapon to operate for a certain length of time without drawing power from the ship. The ability to counter threats at the speed of light and destroy targets for only dollars per shot is a game-changing effect.

C. TECHNOLOGIES

1. Chemical Lasers

There are many types of laser weapons that are able to successfully engage and destroy targets, but they are not all desirable for naval applications. The first type of laser to reach MW power levels was the chemical laser, which operates on the principle of population inversion by an exothermic chemical reaction [1]. These lasers produce harmful exhaust chemicals, tend to be very large, and have magazines limited by the amount of chemicals they can hold. In the recent past, these types of lasers have been utilized by the U.S. Air Force in developmental programs like the Boeing Airborne Laser. Due to the harmful gases and limited magazines, they are not safe or practical for naval applications.

2. Free Electron Lasers

FELs work by sending a beam of relativistic electrons through a magnetic field that causes the electrons to wiggle back and forth and emit light [1]. They are believed to be scalable to the MW level because the gain medium (the relativistic electron beam) is continually replenished. Therefore, there is no concern about damage to the gain medium due to excessive heat. Certain configurations of FELs are tunable to different wavelengths, which enables better propagation through changing atmospheric conditions [1]. They are all-electric weapons that require only ship power to operate, meaning they have an unlimited magazine as long as there is fuel on board. FELs are not a near-term solution due to their current size, lack of power, relative immaturity, and production of ionizing radiation. However, it is believed that this technology may be necessary to engage ballistic or high-speed missile threats from a naval platform.

3. Solid-State Lasers

SSLs are a near-term solution that will allow the Navy to engage certain relevant but slower moving threats (e.g., drones and small craft). SSLs are comprised of a few major components, the first being a pumping source. The pumping source is a laser or flash lamp and is used to excite the bound electrons in the gain medium. This results in a

population inversion, which in turn creates laser light at a certain frequency. Once the population inversion has occurred, laser light is emitted due to the constructive interference of photons generated as electrons drop from an excited state to a less excited state. The frequency of the laser light is dependent on this change in energy and so depends on the type of gain medium. The last major components of many SSLs are the mirrors on both ends of the medium that create a resonant cavity. This allows the power to build up over many passes. One mirror is slightly less than 100 percent reflective so that light can be out coupled and sent to the beam director for use on a target. SSLs are thought to be limited to the sub-MW class due to the thermal restrictions of the gain medium. The higher the output power, the greater the temperature in the medium and the more risk that damage to the medium will occur. SSLs are limited to operating at a single wavelength, but gain media exist that lases at certain wavelengths with superior propagation characteristics. Though their output power is not at the MW level, it has been proven that that kW class lasers can be employed against some of the current threats the Navy faces.

D. LASER WEAPONS SYSTEM

The Navy's recent focus has been on SSLs. It has been able to successfully deploy a Laser Weapon System (LaWS) with an output power of around 35 kW aboard the USS Ponce. The usefulness of this laser has been demonstrated by its abilities to engage targets and seamlessly integrate with the ship's combat systems suite [2]. With the success of LaWS, the Navy has now refocused its efforts to upgrade the output power of the laser to the ~100 kW level and to integrate the laser system into a ship's electrical and plumbing systems.

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III. ATMOSPHERIC PROPAGATION OF HIGH-ENERGY LASERS

A. EXTINCTION

Extinction is comprised of four major components: aerosol scattering, aerosol absorption, molecular scattering and molecular absorption. Absorption can be described as the “capture of photons at one energy level with a resulting re-emission of photons at another, lower, energy level” [1]. Scattering causes photons to be elastically deflected in random directions. The consequences of both processes cause a decrease in the overall energy delivered to the target [1]. These two effects negatively affect HEL performance and must be understood while designing a SSL laser for naval applications.

Beer’s law describes the power $P(z)$ attenuation of the laser light due to scattering and absorption:

$$P(z) = P_0 e^{-\epsilon z} \quad (1)$$

where P_0 is the initial power of the laser, ϵ is the extinction coefficient, and z is the distance traveled.

The extinction coefficient ϵ takes into account scattering and absorption for both molecules and aerosols. Figure 1 shows how ϵ varies with wavelength; it is clear that there are certain wavelengths that intrinsically allow better propagation at $\sim 1 \mu\text{m}$, $1.5 \mu\text{m}$, $2.25 \mu\text{m}$, and $3.5 \mu\text{m}$. The horizontal and vertical axes are log scales, which means that the extinction coefficient is orders of magnitude higher than at the aforementioned propagation wavelengths. For this research, the wavelength 1.0642 microns will be used due to its superior propagation characteristics in maritime environments.

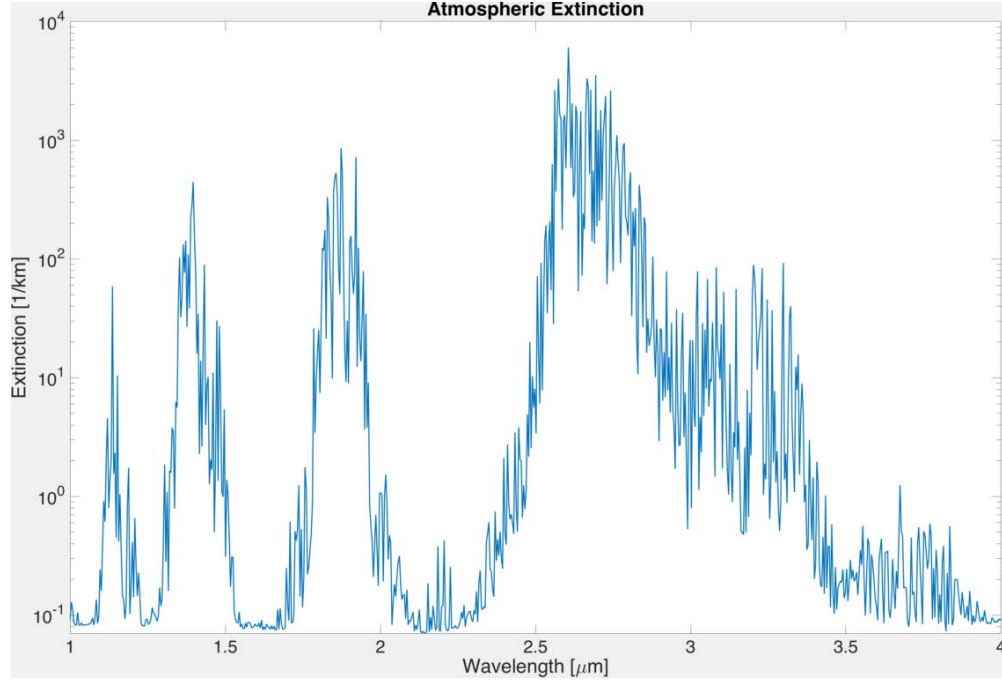


Figure 1. LEEDR results for atmospheric extinction for varying wavelengths in the summer in Bahrain

1. Molecular Absorption and Scattering

Molecular absorption and scattering are due to interactions of photons with the gases in the atmosphere. Molecular absorption comes primarily from H₂O and CO₂ molecules. It depends on the discrete energy levels of the molecules,

$$\Delta E = hf = \frac{hc}{\lambda} , \quad (2)$$

where the change in discrete energy levels is ΔE , h is Planks constant, f is the frequency, λ is the wavelength and c is the speed of light. The extinction due to molecular absorption is heavily dependent on the wavelength of the laser light. Since the Navy operates in a maritime environment, H₂O content (in the form of humidity) is especially important when selecting the laser wavelength. Molecular scattering is a form of Rayleigh scattering, which scales as $1/\lambda^4$ and particle size is much smaller than the wavelength.

2. Aerosol Absorption and Scattering

Aerosols are small particles of liquids or solids in the atmosphere (smoke and water droplets, for example). These, too, have an effect on the attenuation of laser light through the atmosphere. Aerosol density is normally greater at lower altitudes, making the effects of aerosol absorption and scattering more influential at lower altitudes.

Light scattering and absorption for aerosols is described by Mie theory, which is valid when particle size is approximately equal to the wavelength. Mie calculations tend to be intricate and depend on the bulk optical properties of the aerosol as well as the particle size. Overall, the aerosol scattering/absorption coefficients tend to be relatively weak functions of the wavelength relative to molecular absorption.

Comparing the effects of scattering and absorption for both molecules and aerosols, using a program called MODTRAN, Figure 2 shows that for $\lambda = 1.0642\mu\text{m}$, the extinction coefficient is low for molecular absorption, molecular scattering, and aerosol absorption. The effects of molecular absorption and scattering are highly wavelength dependent, whereas aerosol absorption and scattering are not.

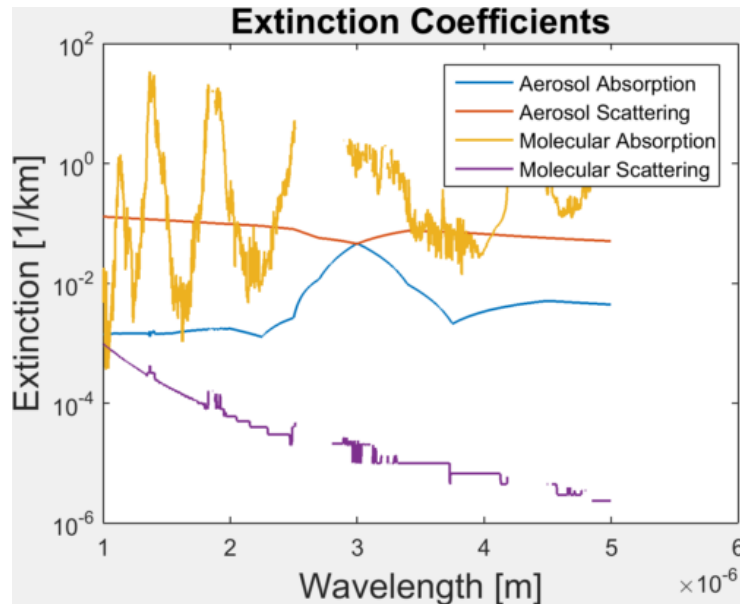


Figure 2. MODTRAN results for extinction for both molecular and aerosol absorption and scattering in a tropical maritime environment with visibility at 23 km

B. TURBULENCE

Turbulence is the result of local variations of the index of refraction of the air due to small changes in the temperature. These variations can disrupt the focus of the laser beam. One of the biggest drivers of turbulence in a marine environment, at altitudes less than 50 m, is the air-sea temperature difference. A larger temperature difference will cause more turbulence.

The total effects of turbulence can be described by the C_n^2 value, which varies in both time and space. These values normally range between $10^{-13} \text{ m}^{-2/3}$, indicating stronger turbulence, to $10^{-17} \text{ m}^{-2/3}$, indicating weaker turbulence. Additionally, the Fried parameter, r_o , incorporates information about C_n^2 along the beam path. For a focused beam, it is defined as

$$r_o = 0.33 \frac{\lambda^{6/5}}{R^{3/5} (C_n^2)^{3/5}} \quad (3)$$

where R is the range to the target. Assuming a constant C_n^2 , the Fried parameter will be larger with a small C_n^2 and small with a large C_n^2 . When Fried initially came up with this parameter, he thought of it “as a diameter above which imaging resolution does not improve with increasing telescope size” [1]. In other words, if the r_o value is smaller than the beam director size, the overall performance of the laser would decrease significantly at the target due to turbulence.

Figures 3 and 4 show the difference between weak turbulence and strong turbulence at a range of 5 km. Comparing the two figures, the effects of turbulence become very apparent. These two figures are snapshots in time of the irradiance at the target. The irradiance pattern in Figure 4 (strong turbulence) will fluctuate randomly. In that case, the peak irradiance on the target can be the same or even higher than the weak turbulence case, but the time averaged irradiance over the entire dwell time will be less.

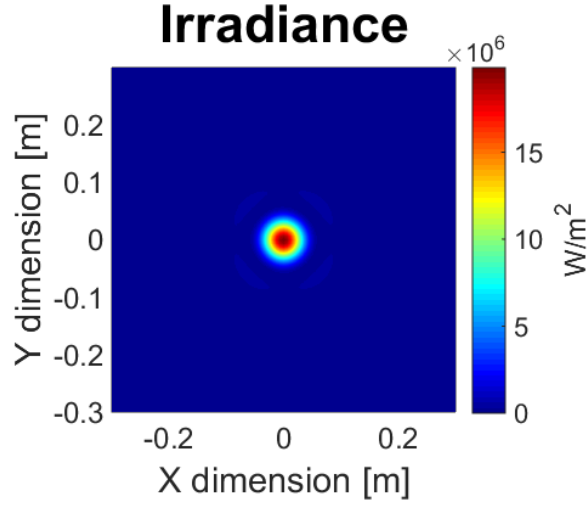


Figure 3. WaveTrain irradiance results for a 100 kW laser, at 1.0642 μm , at 5 km when $C_n^2 = 1 \times 10^{-18} m^{-2/3}$ (weak turbulence)

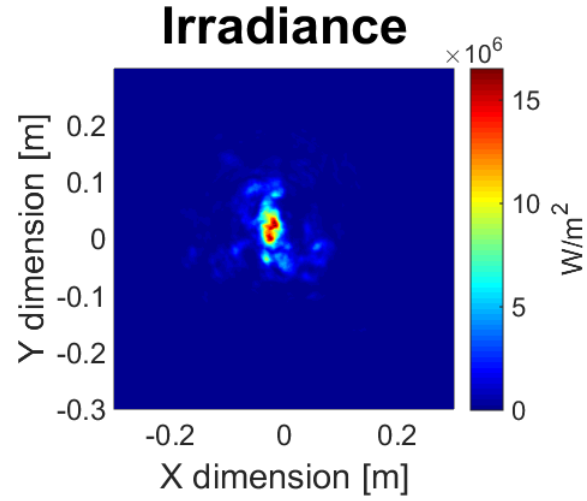


Figure 4. WaveTrain irradiance results for a 100 kW laser, at 1.0642 μm , at 5 km when $C_n^2 = 1 \times 10^{-14} m^{-2/3}$ (strong turbulence)

C. THERMAL BLOOMING

Thermal blooming is a nonlinear effect caused by the heating of the surrounding air, which occurs as the power of the HEL increases. The heating of the air decreases the density of the air and therefore alters the index of refraction, resulting in a change in the

intended propagation path. Specifically, as the temperature of the column of air goes up, the air acts like a diverging lens as shown in Figure 5 [3]. The left side of Figure 5 represents the laser beam as it propagates through the air, while the right side is what the beam would look like on the target after traveling a distance of z .

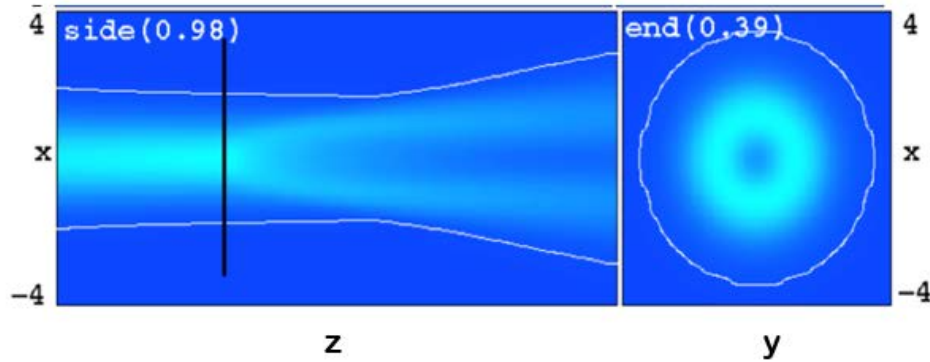


Figure 5. The side view and end view of the effects of thermal blooming

Wind can alter the effects of thermal blooming. Relative motion between the beam and the air introduces cooler air into the path of the beam. As the air crosses the beam, it warms up. This temperature gradient, in addition to acting like a diverging lens, causes the beam to bend into the direction of the wind as shown in Figure 6. For Figure 6, the picture on the left has no wind, while the picture on the right has wind perpendicular to the beam path.

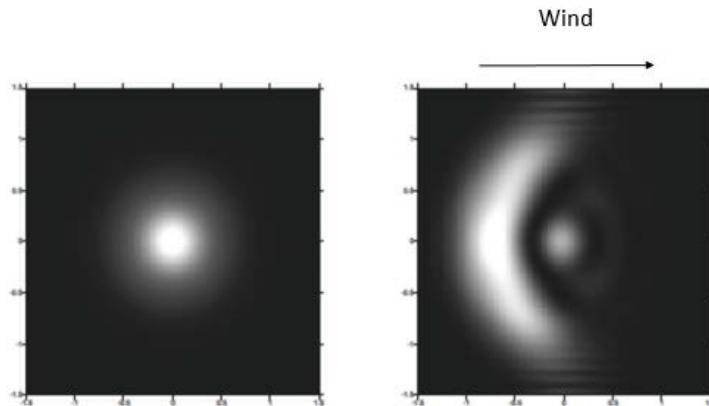


Figure 6. The effects of wind and thermal blooming. Source: [4].

Thermal blooming can be described by equation 4, where N_D is the distortion number, z is the slant path distance, $\alpha(z)$ is the overall absorption coefficient (molecular plus aerosol), and $V_{wind}(z)$ is the effective wind speed perpendicular to the beam. Also, P is the power of the laser beam, k is the wave number, $D(z)$ is the diameter of the beam, ρ_o is the density, c_p is the specific heat, $n_T(z)$ is dn/dt which is the rate of change of the index of refraction with respect to temperature, and $T(z)$ is the beam transmission [1].

$$N_D = -\frac{4\sqrt{2}kP}{\rho_o C_p} \int_{path} \frac{\alpha(z)T(z)n_T(z)}{V_{wind}(z)D(z)} dz \quad (4)$$

The effects of thermal blooming become more prevalent when $N_D > 25$ [1]. Equation 4 indicates how various parameters affect thermal blooming. For example, scenarios with little to no effective wind cause N_D to increase and therefore thermal blooming becomes worse. Considering some of the Navy's possible engagement scenarios (e.g., drones and small boats), understanding the effects of thermal blooming are vital to the successful employment of HELs.

As laser technology continues to mature, there is a strong desire to continue to increase the output power of the laser. However, there may be limitations imposed by thermal blooming on output power in high absorbing regions (e.g., low altitudes and regions of high molecular absorption). Equation 5 can be used to estimate the critical power, P_{crit} , which is the maximum output power which correlates to the maximum irradiance on target for given atmospheric conditions. The constants a and m are dependent on the overall beam shape. Above this P_{crit} , the increased thermal blooming actually reduces target irradiance.

$$P_{crit} = \left(\frac{P}{N_D} \right) \left(\frac{-1}{a(1-m)} \right)^{1/m} \quad (5)$$

Figure 7 shows that up to a certain output power, irradiance on the target continues to increase, but then falls off above P_{crit} . The critical power decreases as the distortion number increases; thus, the same trends that increase N_D will decrease P_{crit} .

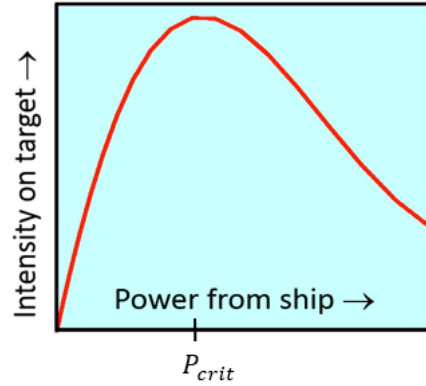


Figure 7. Thermal blooming effects on output power scaling

D. ANCHOR

In order to evaluate different power lasers against varying targets, NPS's Directed Energy Group developed a laser performance code called ANCHOR. This code uses analytical scaling laws that characterize laser performance. Since it uses analytical scaling laws to derive its figures of merits, results are achieved on the order of seconds vice hours when compared to full diffraction codes. This program takes atmospheric inputs from a program called LEEDR.

The figures of merit that ANCHOR produces are time-averaged irradiance, power-in-the-bucket, dwell times, and total number of shots given a prescribed energy storage system. Table 1 shows a list of user defined inputs that will be used in this thesis to study a multitude of different engagement scenarios.

Table 1. User-defined input parameters for ANCHOR

Parameter	Description
Laser power	150, 500, 1000 kW
Wavelength	1.064 μm
Beam quality	$M^2 = 3$
RMS jitter	5 μrad
Beam director diameter	0.3 m
Beam type	Uniform
Beam director height	10 m
Atmospheric data	LEEDR
Wall plug efficiency	20%

IV. DAMAGE MECHANISMS

The losses accrued as laser light travels through the atmosphere is only part of the issue. It is important to understand the interaction of the laser light with the target to understand how damage occurs. When using an HEL to destroy a target, there are two common classifications of kills: hard and soft. A soft kill can be defined as damage to some sub systems of the target that would disturb the target's operation [3]; an example of this kind of kill would be blinding or destroying the seeker of a missile. A hard kill is more traditionally understood as destroying the target (e.g., causing it to disintegrate in flight). For the purpose of this research, only hard kills will be considered; furthermore, as a simplification, a hard kill will be defined as melting a hole through an area of 100 cm^2 . Whether this amount of damage is sufficient to induce a hard kill depends on the specific target. As specific laser/target interaction information is often classified, this will define a constant metric that will facilitate analysis of weapon performance.

In order to melt a portion of the target, enough energy must be deposited onto the material so that it initially reaches its melting point and then melts. This energy must be deposited at a rate that exceeds any loss mechanisms--namely, conductive, convective, and radiative losses. Conductive losses can be described as the flow of energy from hot areas to cold [3]. Convective losses are those that occur by air flowing over the target. Radiative losses occur as the target area heats up and emits as blackbody.

The set of equations used in the following pages are rough estimates that can be used to determine the dwell time necessary to destroy the target. The first thing that has to be calculated is the energy needed to reach the melting point,

$$Q_1 = c_p m \Delta T , \quad (6)$$

where c_p is the specific heat, m is the mass of the necessary volume of material to constitute a hard kill, and ΔT is the difference in temperature between the melting temperature and the temperature of the environment. The energy needed to melt the material at its melting point is,

$$Q_2 = m\Delta H , \quad (7)$$

where ΔH is the heat of fusion for a given material. The total energy needed to melt a given material is therefore just the sum of Q_1 and Q_2 :

$$Q_{melt} = Q_1 + Q_2 . \quad (8)$$

Next, we consider the loss mechanisms. The power radiated away as a blackbody is

$$P_{rad} = \varepsilon\sigma A_f (T_{melt}^4 - T_{environment}^4) , \quad (9)$$

where ε is the emissivity, σ is Stefan-Boltzmann's constant, A_f is the frontal area, and T_{melt} and $T_{environment}$ are the associated temperatures in Kelvin. The power conducted away can be estimated by

$$P_{cond} = kA_s (T_{melt} - T_{environment}) / \Delta x , \quad (10)$$

where k is the thermal conductivity, A_s is the side area, and Δx is the distance of the temperature gradient. The total power lost from these mechanisms is then

$$P_{loss} = P_{rad} + P_{cond} . \quad (11)$$

Now that the energy required to destroy the target and the loss mechanisms have been calculated, the required dwell time can be determined

$$T_d = \frac{Q_{melt}}{(P_{bucket} \times f_{tgt}) - P_{loss}} , \quad (12)$$

where P_{bucket} is the power deposited in the target area, and f_{tgt} is the fractional target absorption. Equations 1 through 7 can be applied to any material and scenario in order to get a reasonable order of magnitude estimate of what the necessary dwell time would be for a given power-in-the-bucket. When the power-in-the-bucket multiplied by f_{tgt} does not exceed P_{loss} , the dwell time diverges and obtaining a hard kill is no longer possible.

Now that the general equations have been presented it is important to do a few examples to get an idea of possible dwell times. For the purposes of illustration, consider a 3 mm thick aluminum sheet (as shown in Figure 8). We define the bucket as the region on the target we wish to melt to sufficiently to induce a hard kill; in this example, the bucket diameter is 10 cm (red cylinder in Figure 8). Further, suppose that the laser has sufficient output power to deliver 60 kW within this bucket area. The material parameters for aluminum (Table 1) can be used to solve Equations 1 through 7 and achieve the results in Table 2.

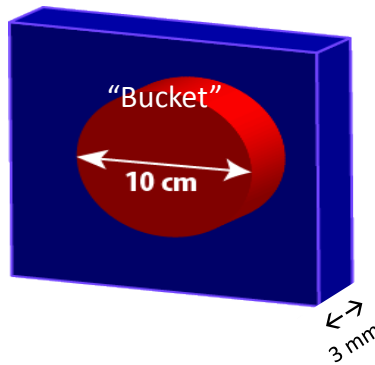


Figure 8. Aluminum sheet, 3 mm thick

Table 2. Damage physics parameters for 3 mm thick aluminum

Parameter	Description	Value
c_p	Specific heat	904 J/kgK
m	Mass	0.063 kg
ΔH	Heat of fusion	387 J/g
ϵ	Emissivity	0.2
A_f	Area(frontal)	0.0078 m ²
A_s	Area (side)	9.42x10 ⁻⁴ m ²
T_{melt}	Target melting point	933 K
$T_{environment}$	Temperature of environment	298 K
ΔT	Change in temperature	635 K
k	Thermal conductivity	210 W/mK
Δx	Distance of temperature gradient	0.02 m
f_{tgt}	Fractional target absorption	0.2
σ	Stefan – boltzmann constant	5.67x10 ⁻⁸ W/m ² K ⁴

After doing the calculations, it is easy to see that the power conducted away is the dominate term for losses. In this example, the power in the bucket (60 kW) exceeds the total losses (7.3 kW), and the target is melted in approximately 13 seconds.

For another example, we keep all of the parameters the same except change the material to titanium (Table 3).

Table 3. Calculated values for 3 mm thick aluminum

Parameter	Value
Q_1	37 kJ
Q_2	24 kJ
Q_{melt}	61 kJ
P_{rad}	66 W
P_{cond}	6.3 kW
P_{loss}	7 kW
T_d	13 sec

Plugging in the given parameters into the previously mentioned equations, the following values are achieved as shown in Table 4 and Table 5.

Table 4. Damage physics parameters for 3 mm thick titanium

Parameter	Description	Value
c_p	Specific heat	528 J/kgK
m	Mass	0.106 kg
ΔH	Heat of fussion	435 J/g
ε	Emissivity	0.63
A_f	Area(frontal)	0.0078 m ²
A_s	Area (side)	9.42x10 ⁻⁴ m ²
T_{melt}	Target melting point	1923 K
$T_{\text{environment}}$	Temparature of environment	298 K
ΔT	Change in temperature	1625 K
k	Thermal conductivity	17 W/mK
Δx	Distance of temperature gradient	0.02 m
f_{target}	Fractional target absorption	0.2
σ	Stefan – boltzmann constant	5.67x10 ⁻⁸ W/m ² K ⁴

Table 5. Calculated values for 3 mm thick titanium

Parameter	Value
Q_1	91 kJ
Q_2	46 kJ
Q_{melt}	137 kJ
P_{rad}	3.8 kW
P_{cond}	1.3 kW
P_{loss}	5.1 kW
T_d	20 sec

Comparing these values to aluminum, it is clear to see that one of the reasons the dwell times are higher is because the energy needed to melt the target is almost double that of aluminum. Every target will have different properties and vulnerabilities, including those constructed from same types of materials. Therefore, these kinds of calculations should be considered “ballpark” estimates that we will use for other aspects of our analysis.

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V. THE REASON FOR ENERGY STORAGE

The DDG-51 Arleigh Burke class destroyer has three gas turbine generators that each output 2500 kW, totaling 7.5 MW of power. However, since the ship has an advanced combat systems suite and a large power demand throughout the ship, there is only 150 kW of available power. HELs require an exorbitant amount of energy, on the order of ~100 kW to MWs of power, and because of this, an energy storage system is necessary in order to operate them. The amount of energy storage that is needed is dependent on the overall wall plug efficiency of the laser system and the output power of the laser. For example, most laser systems have a wall plug efficiency of about 20 to 30 percent, which means that a laser with an output of 100 kW would need between 300 kW and 500 kW of power to operate. This is more energy than a ship can provide, so the use of an energy storage system is vital to the successful integration of HELs onto naval platforms.

There are many different types of energy storage technologies including, but not limited to, batteries and flywheels. When thinking about energy storage, there are two main attributes to consider, energy density and power density. Energy density is the amount of energy that can be stored compared to the weight or size, while power density is how quickly the stored energy can be released compared to the weight or size. Figure 9 shows how different energy storage systems compare to one another in terms of these density characteristics. The ideal case would be to have an energy storage system that has both the highest energy and power density (top right corner). However, nothing exists in this region, so tradeoffs have to be made. For this study, we will focus primarily on lead acid and lithium-ion batteries. They are a safe, near-term solution that offer a good mixture of energy and power density.

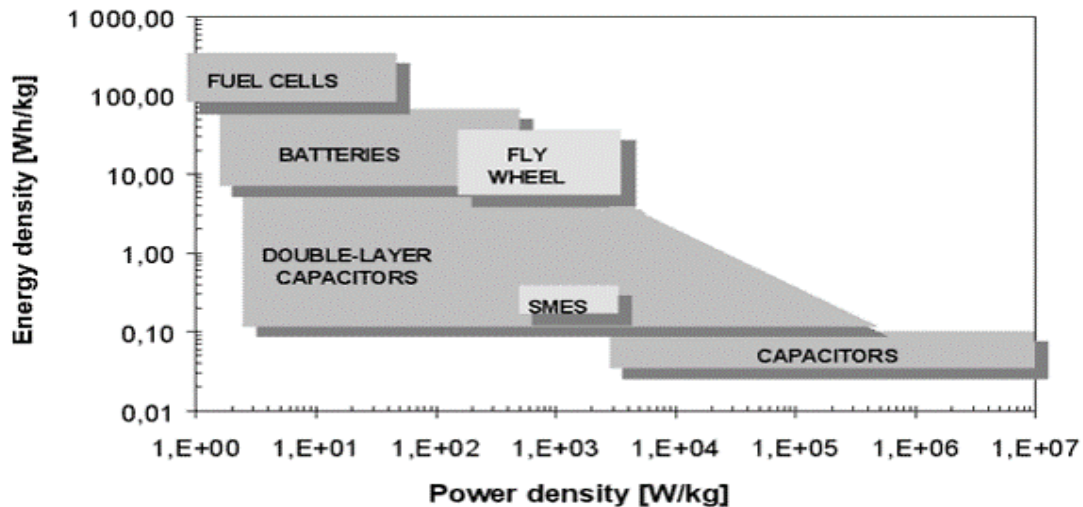


Figure 9. Energy storage options based on energy density vs. power density.
Source: [5].

A. LEAD ACID BATTERIES

Lead acid batteries are a mature and safe technology that are already on board Navy ships. As seen in Figure 9, batteries have a relatively high energy density and a low to medium power density. Lead acid batteries have a total energy density of $\sim 200 \text{ MJ/m}^3$ [6]. Key attributes are that lead acid batteries tend to take on the order of hours to recharge and should not be discharged lower than 50 percent due to the reduced life cycle of the battery that will ensue.

B. LI-ION BATTERIES

A newer technology is lithium-ion batteries, which have a much higher energy density ($\sim 1000 \text{ MJ/m}^3$) and a better discharge tolerance (~ 80 to 90 percent). Li-ion batteries work under the same simple premise of transferring ions to electrodes during the charging and discharging periods [7]. Since the energy density is almost 5 times greater than that of a lead acid battery, the overall weight and volume is significantly less than that of a lead acid system; they also charge faster than lead acid batteries, which makes them an appealing alternative. However, lithium-ion batteries have been known to be potential fire hazards, which could make their relevance as an energy storage system questionable [8].

C. FLYWHEELS

Flywheels are similar to batteries with respect to energy density but have a much higher power density. A flywheel is a device that rotates at very high speeds (~60,000 rpm) that can convert this mechanical energy into electrical energy [9]. Flywheels can charge and discharge rapidly, which is ideal for multi-shot engagements (i.e., swarm attacks). A drawback to flywheels is there are no commercial off the shelf solutions available, so the energy storage system would have to be specifically designed for the platform.

D. ENERGY STORAGE OVERVIEW

Figure 10 is a picture of the major components that would encompass a ship's electrical bus (in this case, a DDG-51 class destroyer), an energy storage system, and a laser weapon system. This figure can be broken down into several major components, including the AC-to-DC converter that converts 450 VAC from the ship's main bus to 1000 VDC that is used to charge the energy storage device, the DC-to-DC converter that converts 1000 VDC to 240 VDC that is needed by the HEL, and the rest of the electrical outline of a DDG-51 class destroyer.

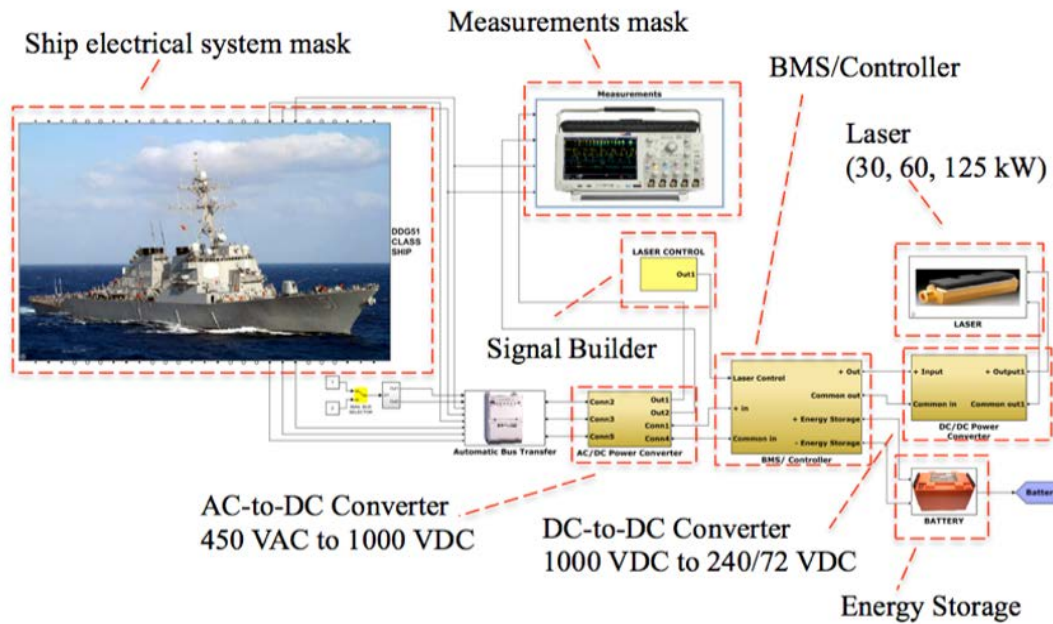


Figure 10. Diagram of major components of a laser weapons system and ship components

Energy storage systems that were used for this research were lead acid batteries and lithium-ion batteries. For the lead acid batteries (Figure 11), a string is defined as one hundred 12V batteries. For the lithium ion batteries (Figure 12), a string is defined as two hundred seventy 3.3 V batteries. In order for the energy storage system to be viable, it must have a nominal voltage of ~1000 V, thus the reason for 100 lead acid batteries and 270 lithium ion batteries for a string.



Figure 11. XE 70 Genesis battery (lead acid)



Figure 12. Saft VL 30 PFe lithium ion battery

Tables 6 and 7 give the basic properties of the batteries that will be used for the following simulations. One string of lead acid batteries weighs approximately 2500 kg, has ~150 MJ of energy, and takes up ~ 1 m³ of space. For 1 m³ of lithium-ion batteries, 7 strings, there will be ~750 MJ of energy, and a weight of ~2200 kg.

Table 6. Properties of lead acid battery Genesis XE 70

Lead Acid Battery: Genesis XE70			
Volume (m ³)	Mass (kg)	Energy (Wh)	Volts
10 ⁻²	25	800	12

Table 7. Properties of lithium-ion battery VL-30 PFe

Lithium-ion Battery: VL-30 PFe			
Volume (m ³)	Mass (kg)	Energy (Wh)	Volts
5x10 ⁻⁴	1.1	110	3.6

At first glance, the amount of available energy in the 1 m³ of lithium ion batteries is five times greater than that of the lead acid; however, that is not necessarily the case. Based on the simulations and the general characteristics of each battery, the life cycle of a lead acid battery not only decreases when discharged below 50%, but it also discharges at a slightly different rate. Similarly, when lithium-ion batteries are discharged below 20%, the discharge rate changes. For the purpose of this research, lead acid batteries will not be discharged below 50% and lithium-ion below 20%. Taking these conditions into account,

1 m³ of lead acid batteries (1 string) has 75 MJ of energy available while 1 m³ of lithium-ion (7 strings) has 600 MJ of energy available. With that being said, the amount of energy available is ~8 times more for an equal volume of lithium-ion batteries.

VI. RESULTS

The comparisons of 150 kW, 500 kW, and 1 MW lasers were done in two locations: off the coast of Russia and off the coast of Cuba. The atmospheric information came from LEEDR, where the preset for a moderate winter day was selected. The laser parameters listed in Table 1 were used in ANCHOR for these scenarios.

ANCHOR provides the following figures of merit: time averaged irradiance, power in the bucket, and dwell times. Another useful figure of merit that was added to the original ANCHOR code is “shot count,” which is the total number of possible kills on a certain target for a given energy storage system. A shot will be defined as the time necessary to burn a 10 cm hole in a 3 mm thick aluminum sheet at normal incidence. The material properties and loss mechanisms from Table 2 and Table 3 will be used along with the energy storage properties of lead acid and lithium-ion batteries given in Tables 6 and 7 to estimate the shot count in ANCHOR. The motivation for this study is to understand the capabilities of the different power lasers given certain atmospheric conditions against threats like swarm attacks, when there might not be enough time to recharge the energy storage device.

For this study, a volume of 1 m³ of lead acid and lithium ion batteries will be used. The volume here refers only to the space occupied by the physical batteries, and not any cooling or other ancillary equipment. One string of lead acid batteries is 100 batteries, which is equal to 1 m³ and a nominal voltage of 1000 V. One string of lithium-ion batteries is equal to 270 batteries with a nominal voltage of 1000 V. In order to have 1 m³ of lithium-ion batteries, seven strings of lithium-ion batteries will be paralleled together. The total amount of stored energy for 1 m³ of lead acid batteries is 150 MJ and 750 MJ for 1 m³ of lithium-ion batteries. In these scenarios, the lead acid batteries will not be discharged lower than 50 percent and the lithium-ion below 20 percent. This gives the lead acid system 75 MJ of useable stored energy and the lithium-ion 600 MJ of usable stored energy.

A. FIGURES OF MERIT

1. Irradiance

Time averaged irradiance is the first figure of merit from ANCHOR. Figure 13 shows a vertical slice of the atmosphere with the ship being placed at origin. The horizontal axis is the cross range away from the ship, the vertical axis is the altitude above the water, and the color indicates the time-averaged irradiance, using the log scale shown in the color-bar on the right. The black contour lines on the graph indicate different irradiance thresholds. For this example, the contour lines correspond to irradiances of 10 MW/m^2 , 5 MW/m^2 , and 1 MW/m^2 , starting from the left side of the graph and moving to the right. These lines can represent approximate kill thresholds against notional harder targets (for 10 MW/m^2) to softer targets (1 MW/m^2). These lines also can be used as quick references for the user when comparing different plots. For example, the 10 MW/m^2 line tells the user that harder targets can be engaged inside of this line while softer targets can be engaged farther out.

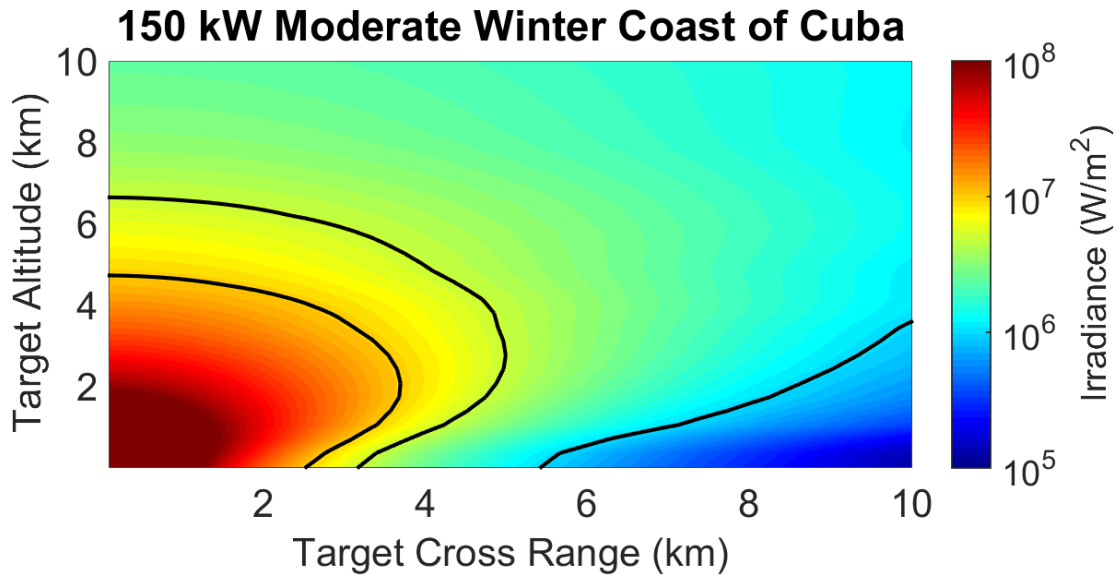


Figure 13. ANCHOR: Time-averaged irradiance plot vs. target range and altitude

2. Power-in-the-Bucket

The next figure of merit that is produced by ANCHOR is time-averaged power-in-the-bucket. As mentioned previously, the power-in-the-bucket is the amount of power that is deposited in a prescribed area on the target. Figure 14 is similar in appearance to Figure 13, but they describe two different things. In order to produce this figure, a bucket size has to be prescribed; in this case, the bucket is defined as a circle with a radius of 5 cm. Similarly to Figure 13, the horizontal and vertical axes represent the target range and altitude away from the ship, respectively. The color indicates the amount of power from the laser that falls within the 5 cm radius bucket, using the log scale shown in the color bar on the right.

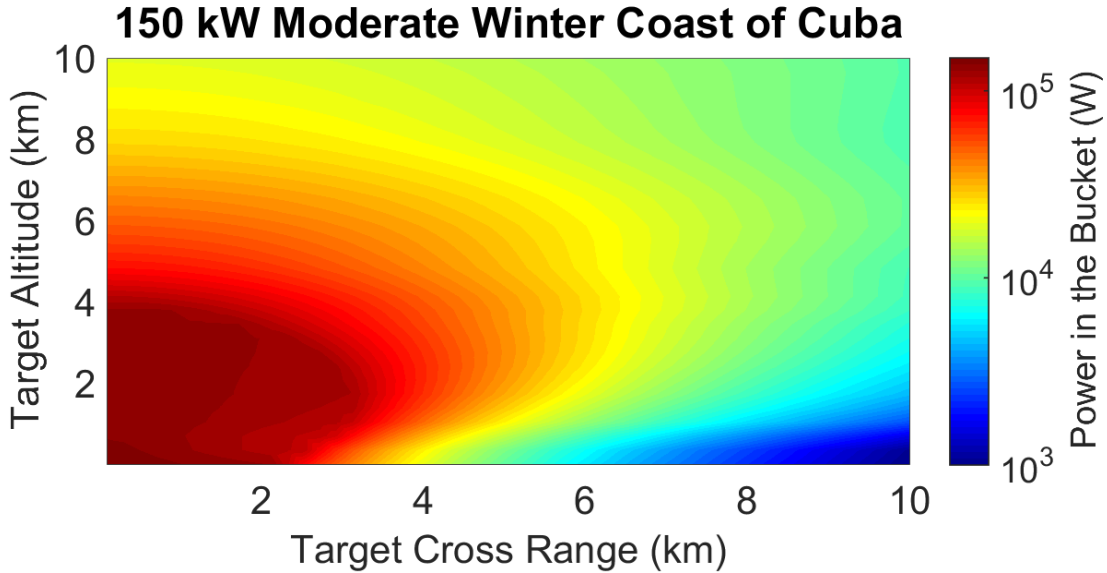


Figure 14. ANCHOR: Power-in-the-bucket plot vs. target range and altitude

3. Dwell Time

Figure 15 is a graph of the dwell time needed to kill a target. In order to display this graphically, the total energy needed to melt the target and the total losses need to be known. For this example, the target will be a 3 mm thick aluminum sheet and the values from Table 2 and Table 3 will be used. Like Figure 13 and Figure 14, the horizontal and vertical axes represent the target cross range and altitude away from the ship. The color

shows the dwell time in seconds shown in the color bar on the right. The black line on this graph indicates a hard kill with a 10 sec dwell time. Just beyond that line the graph turns to solid red, indicating that there is not enough energy being deposited, regardless of the dwell time, to destroy the given target. Inside of the black line indicates that the dwell time will be less than 10 secs to achieve a hard kill on the target.

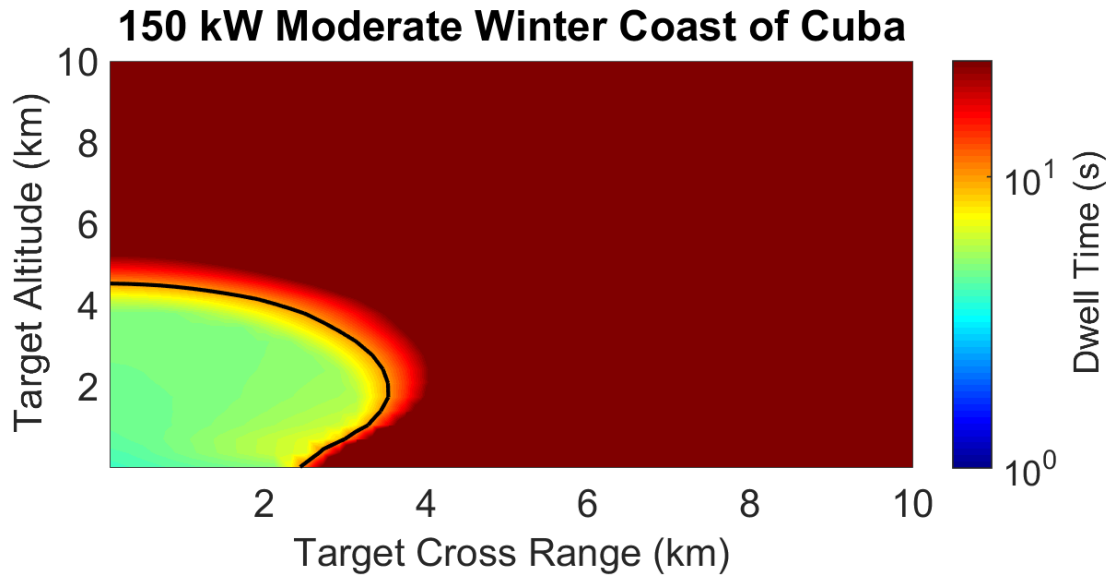


Figure 15. ANCHOR: Dwell time plot vs. target range and altitude

All three of these plots have their own relative merits. The time-averaged irradiance plot (Figure 13) indicates if there is enough power per unit area on the target to cause damage while Figure 14, the power-in-the-bucket plot, shows how much power is deposited into a prescribed area on the target. The difference between these two is that the prescribed area for power-in-the-bucket allows the user to define how large or small an area must be engaged to potentially destroy the target. The dwell time plot (Figure 15) takes into account the prescribed area and calculated losses to determine how much time is needed to destroy the target.

4. Shot Count for Moderate Winter off the Coast of Cuba for Varying Energy Storage Systems and Laser Output Powers

This section will compare the difference in shot counts for 150 kW, 500 kW, and 1 MW lasers versus the type of energy storage system. In order to determine the shot count, Equations 13 and 14 were used, where E_{shot} is the energy per shot, S_{count} is the shot count, P_{laser} is the output power of the laser, W_{eff} is the wall plug efficiency, T_d is the dwell time, and E_{avail} is the energy available in a given energy storage system. Similar to the aforementioned graphs, Figure 16, the horizontal and vertical axes indicate the target cross range and altitude away from the ship. The color shows the number of available shots per the given scenario, according to the color scale shown on the right.

$$E_{shot} = \frac{P_{laser}}{W_{eff}} T_d \quad (13)$$

$$S_{count} = \frac{E_{avail}}{E_{shot}} \quad (14)$$

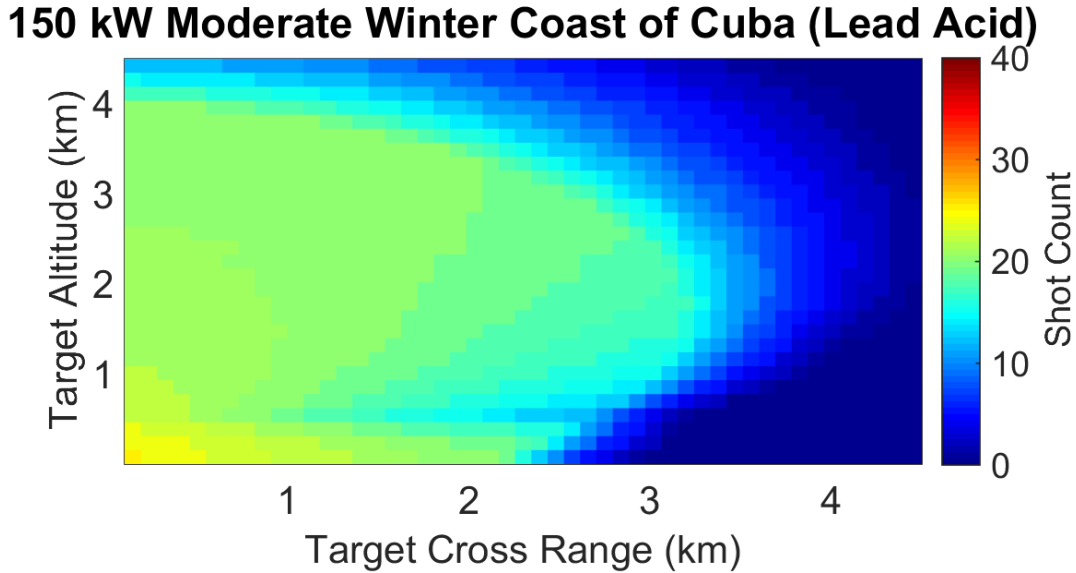


Figure 16. Shot count vs. target range and altitude: 150 kW moderate winter off the coast of Cuba (lead acid)

As the target range and altitude increases, the irradiance at the target decreases, so a longer dwell time is required for a successful kill, and thus there are fewer available shots for a given energy storage configuration.

500 kW Moderate Winter Coast of Cuba (Lead Acid)

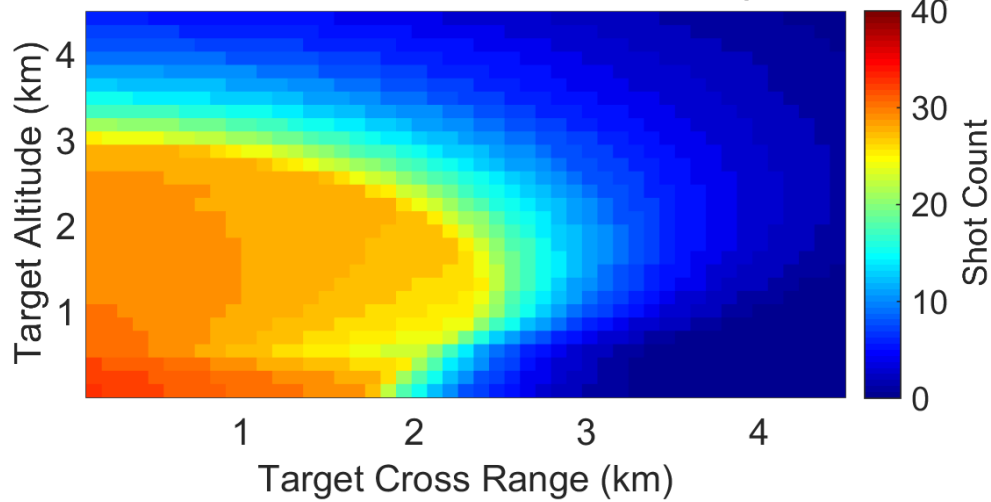


Figure 17. Shot count vs. target range and altitude: 500 kW moderate winter off the coast of Cuba (lead acid)

1 MW Moderate Winter Coast of Cuba (Lead Acid)

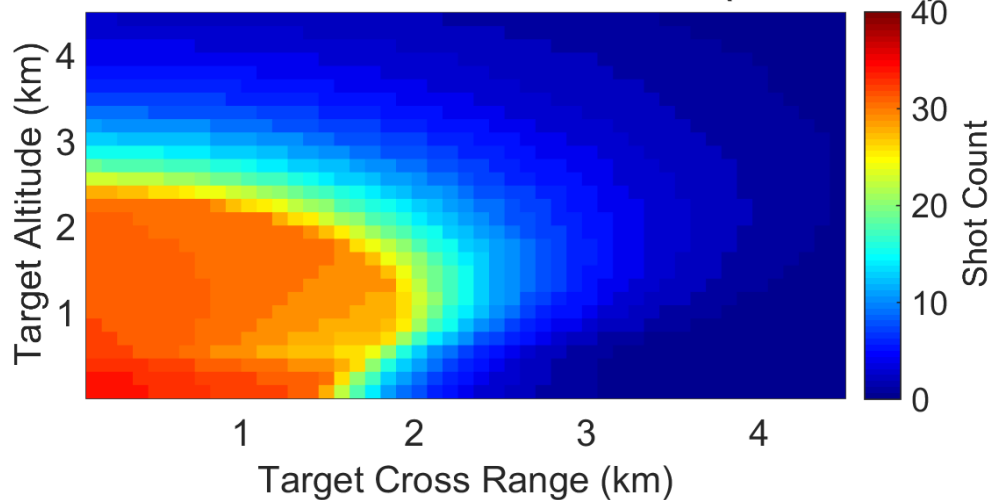


Figure 18. Shot count vs. target range and altitude: 1 MW moderate winter off the coast of Cuba (lead acid)

For Figures 16, 17, and 18, the laser output power increases from 150 kW to 1 MW but the overall effective range stays constant. Regardless of the output power, the figures show that the 3mm thick aluminum will not be destroyed at ranges around 4 km and further. The effects of thermal blooming limit the overall range at which a target can be successfully engaged. However, as the output power is increased the shot count goes up at closer ranges. For example, in Figure 16 at a range of 1 km out and 1 km high, the total number of kills is ~ 20, where as in Figure 18 the shot count is ~ 30.

The next set of graphs (Figures 19 to 21) illustrates the same range of laser output power at the same location, but this time with lithium-ion as the energy storage system. Though the energy storage device is different, the same trends should exist. If the laser power is low, then power-in-the-bucket is not much larger than the losses, which means dwell times will go up, energy per shot will go up, and the total number of shots will go down. Similarly, if the power is too high, thermal blooming will cause the power-in-the-bucket to decrease, the dwell time to go up, the energy per shot to go up, and the overall shot count to decrease.

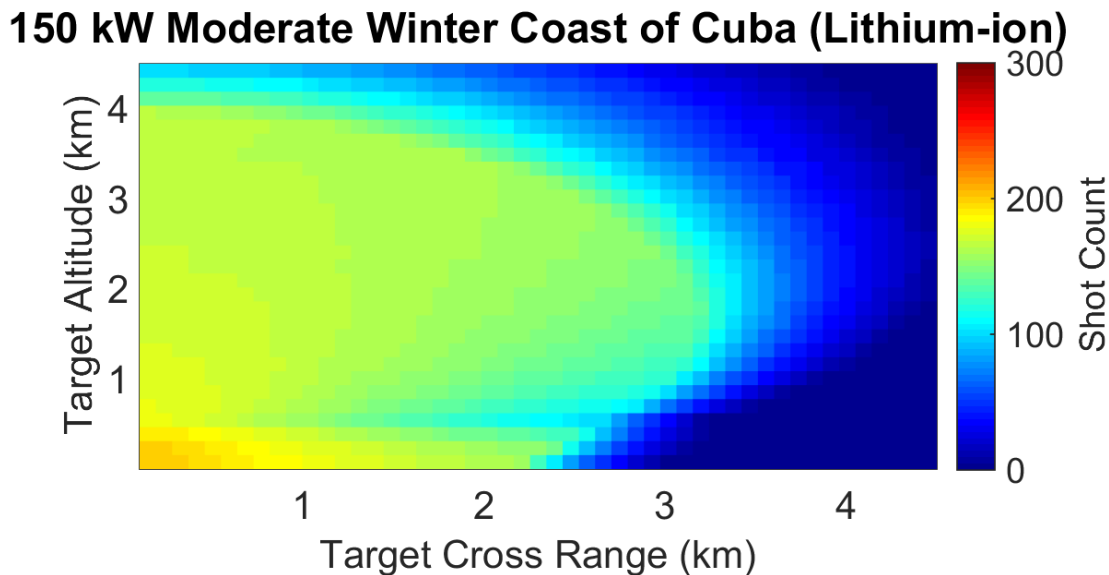


Figure 19. Shot count vs. target range and altitude: 150 kW moderate winter off the coast of Cuba (Li-ion)

500 kW Moderate Winter Coast of Cuba (Lithium-ion)

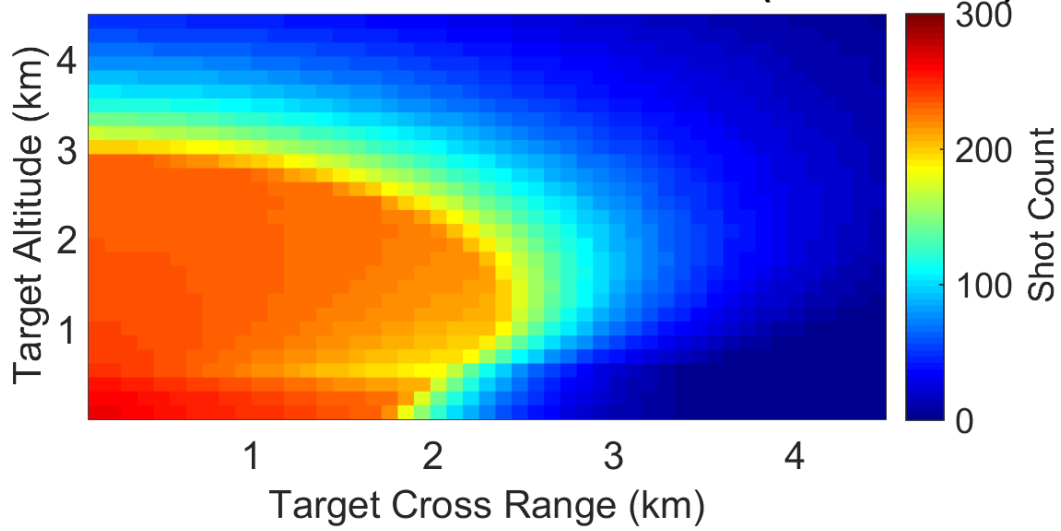


Figure 20. Shot count vs. target range and altitude: 500 kW moderate winter off the coast of Cuba (Li-ion)

1 MW Moderate Winter Coast of Cuba (Lithium-ion)

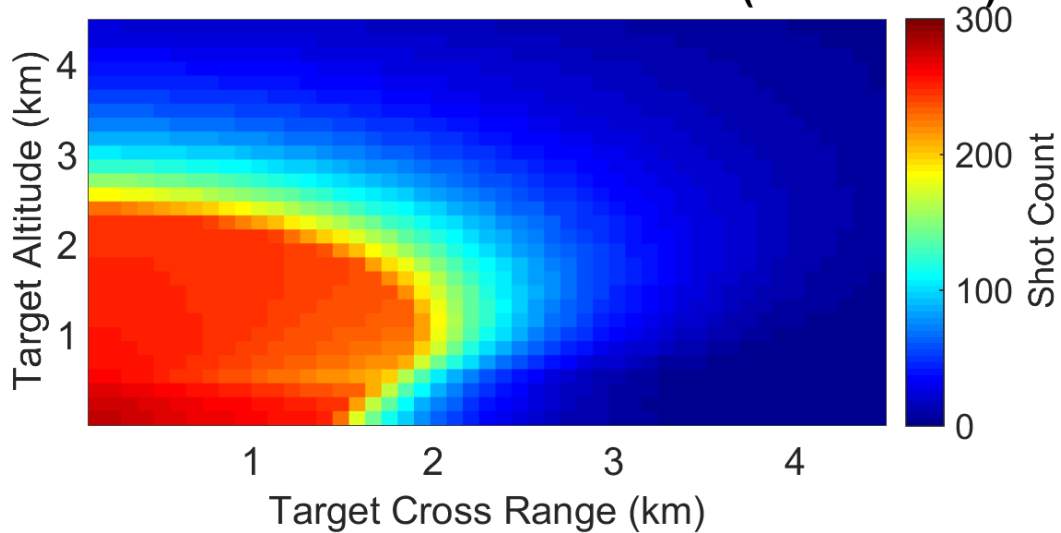


Figure 21. Shot count vs. target range and altitude: 1 MW moderate winter off the coast of Cuba (Li-ion)

Regardless of output power, the overall shot count for the lithium-ion batteries is ~ 8 times greater than the lead acid batteries. For example, in Figure 18, at a range of 2 km out and 2 km high the shot count is ~ 20, where as in Figure 21, the shot count is ~ 160. This was the expected result given the energy density and discharge characteristics of lithium-ion batteries. Again, overall trends in maximizing shot count are the same regardless of battery type.

5. Shot Count for Moderate Winter off the Coast of Russia for Varying Energy Storage Systems and Laser Output Powers

The following scenario is similar to the one described in the previous section, with the only difference being a change in location. This scenario will compare the shot counts of a 150 kW, 500 kW, and 1 MW output power laser off the coast of Russia with moderate winter conditions. The energy storage systems will still be 1 m³ of lead acid and lithium-ion batteries.

Comparing Figures 22 to 24 with Figures 16 through 18, similar trends are noticed. For this example, the effects of thermal blooming are more evident. As the output power increases from 500 kW to 1 MW, the effective range of the laser noticeably starts to decrease. As well as this, the trend of increased shot counts at closer range are obvious. Looking at Figure 22 at a range of 1 km out and 1 km high, the shot count is ~ 25 where as in Figure 24 at the same ranges, the shot count is ~ 35.

150 kW Moderate Winter Coast of Russia (Lead Acid)

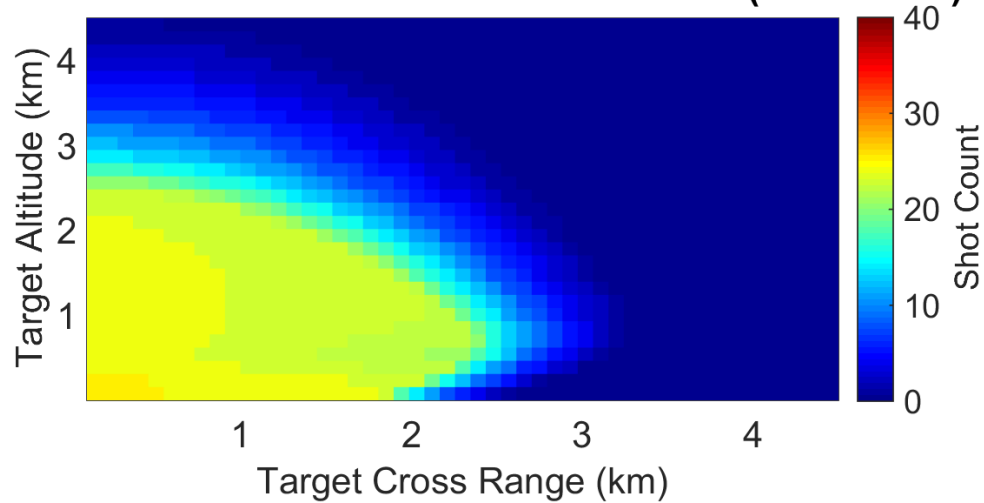


Figure 22. Shot count vs. target range and altitude: 150 kW moderate winter off the coast of Russia (lead acid)

500 kW Moderate Winter Coast of Russia (Lead Acid)

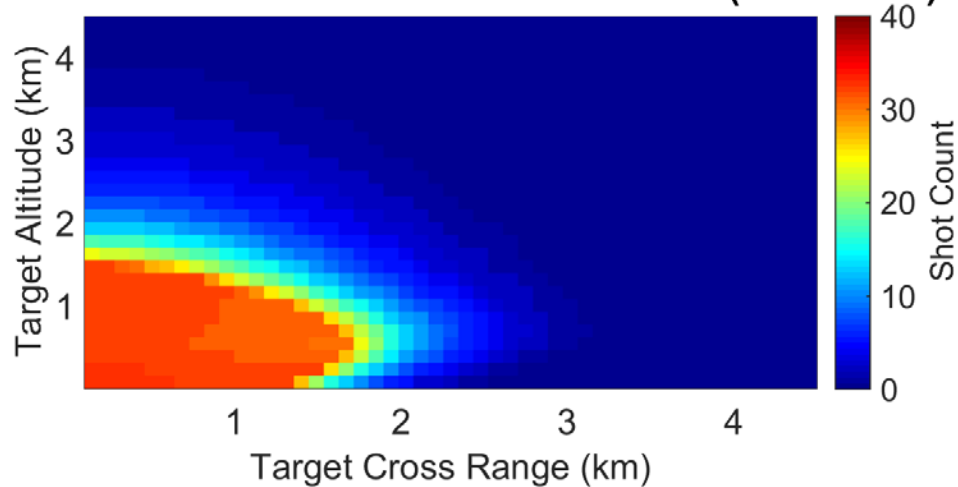


Figure 23. Shot count vs. target range and altitude: 500 kW moderate winter off the coast of Russia (lead acid)

1 MW Moderate Winter Coast of Russia (Lead Acid)

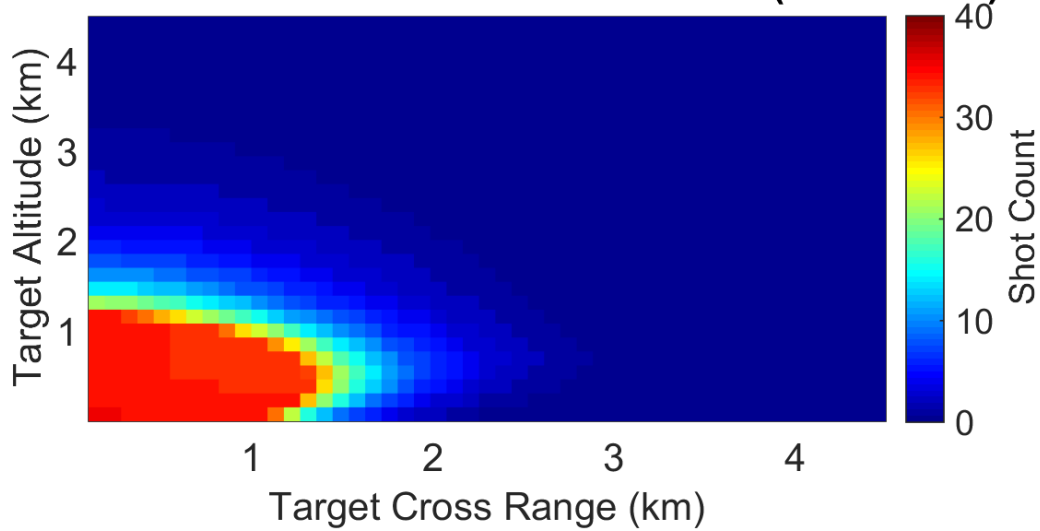


Figure 24. Shot count vs. target range and altitude: 1 MW moderate winter off the coast of Russia (lead acid)

Figures 25 through 27 show the corresponding results for lithium-ion batteries.

50 kW Moderate Winter Coast of Russia (Lithium-ion)

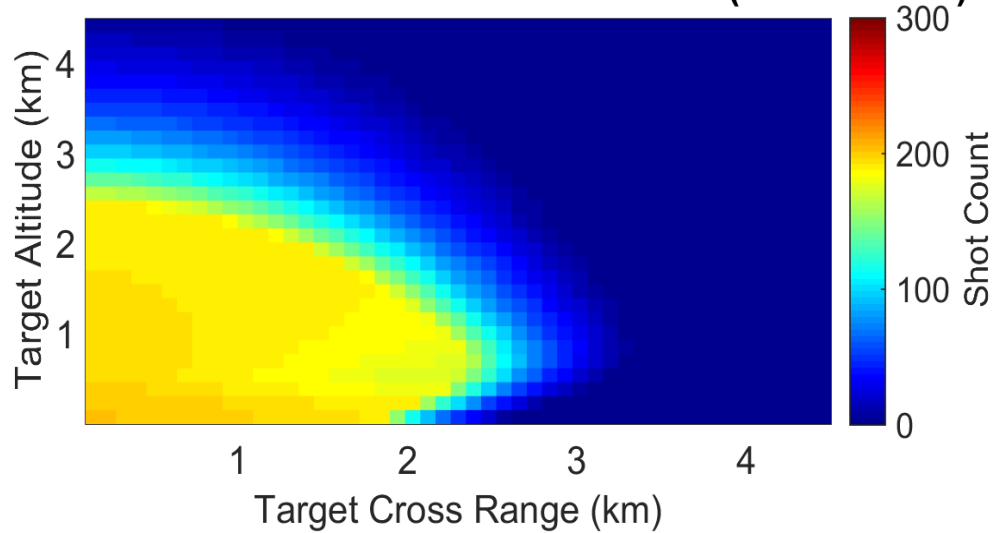


Figure 25. Shot count vs. target range and altitude: 150 kW moderate winter off the coast of Russia (Li-ion)

500 kW Moderate Winter Coast of Russia (Lithium-ion)

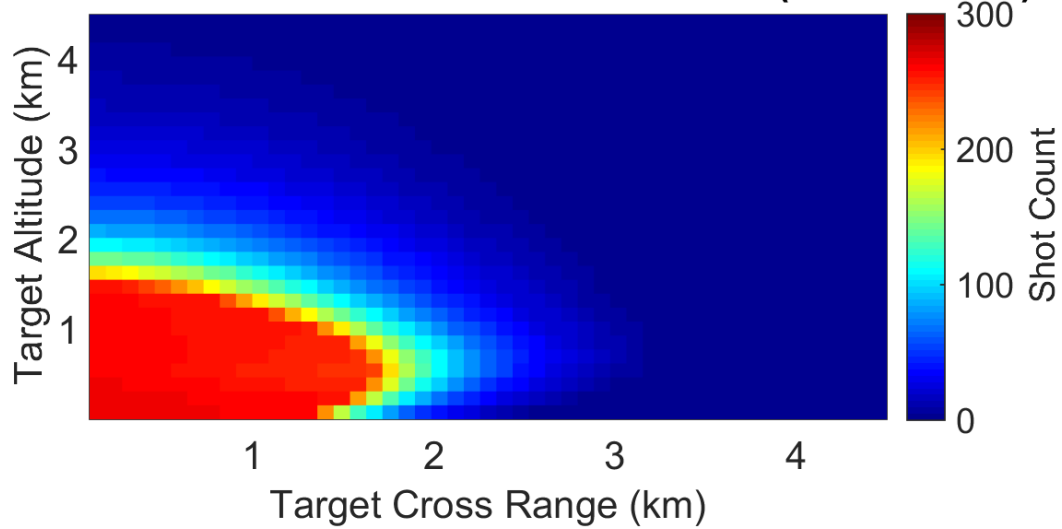


Figure 26. Shot count vs. target range and altitude: 500 kW moderate winter off the coast of Russia (Li-ion)

1 MW Moderate Winter Coast of Russia (Lithium-ion)

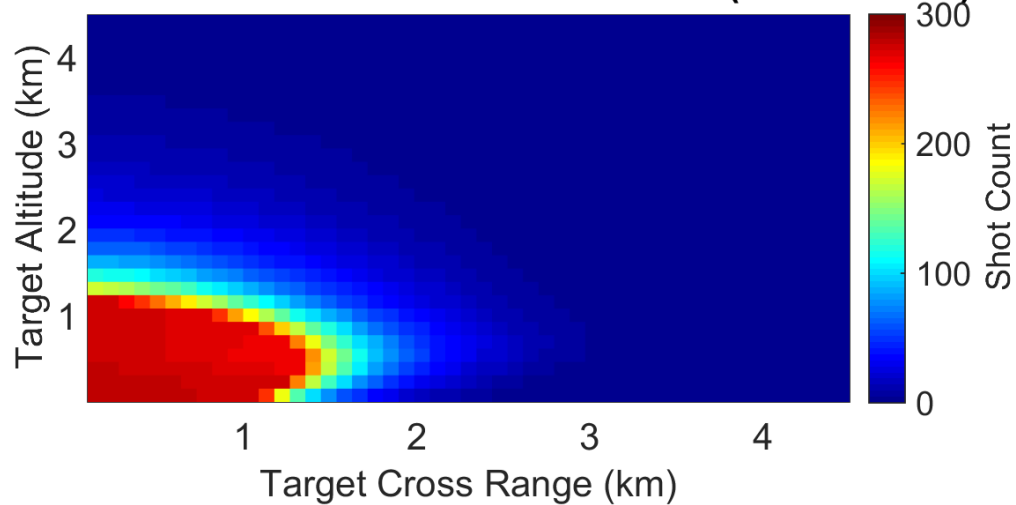


Figure 27. Shot count vs. target range and altitude: 1 MW moderate winter off the coast of Russia (Li-ion)

The overall trends are similar, but the shot count is ~ 8 times that of the lead acid system.

VII. CONCLUSION

HELs are cost-efficient weapons that can have a well-defined place in the arsenal onboard U.S. ships. The main topic of study was how the atmosphere and energy storage system can alter the shot count of different output power lasers. The general trends show that thermal blooming starts to decrease the overall shot count at large ranges ($>$ a few km) as the power is increased, but at closer ranges (< 1 km) the shot count improves with increased output power. What this means is that 500 kW and 1 MW lasers may be better suited for things like swarm attacks close to the ship, while a 150 kW laser might deliver more kills for targets farther away. Of course, which power is optimum depends on the target and weather. Furthermore, a 1 MW laser can, in principle, dial back its output power to increase the shot count at larger ranges if it would be advantageous.

The second focus of this study was energy storage. The benefits of lithium-ion batteries are clear; they are lighter, provide more shots, and have the ability to recharge at a faster rate. Lead acid batteries are significantly bigger, recharge slower, and provide fewer shots for a given volume. However, they are a safe alternative and are a proven technology that is already onboard naval platforms.

Future work for these topics include the study of relative platform and target motion and its effects on thermal blooming.

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